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Interim Scientific Report, 15 Apr 79 - 14 Apr 80

CHEMICAL REACTIONS IN TURBULENT MIXING

AFOSR Contract No. F49620-79-C-0159

15 April 1979 - 14 April 1980

by

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25 Jun 80

SUMMARY

The combustion facility (H_2-F_2) is now nearing completion. As of this writing, a high speed mixing layer has been realized in the test section, using high pressure air. This certifies the flow facility down to and including the test section.

Preliminary results on the effect of high heat release in a turbulent mixing zone were obtained in the NO-O_3 experiment. These results are consistent with predictions based on previously measured p.d.f.'s in non-reacting mixing layers, but in conspicuous disagreements with a variety of accepted model calculations. These results demonstrate again the important influence of the large scale coherent structures on chemical reactions in turbulent flows.

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The first four channels of the multi-channel laser Doppler velocimetry system are essentially completed. The first experiments using this new development are expected in the course of this summer. Digital image analysis of particle streak photography has also been explored as a direct means of two-dimensional measurements of the velocity field in a plane. Finally, a prototype system using a 100 element acoustic detector array has been completed. Initial measurements with four of these channels using 300 kHz sound have been successfully made.

INTRODUCTION

The earlier work on chemical reactions in turbulent mixing which preceded that reported here was summarized in the final technical report of AFOSR Contract No. F44620-76-C-0046. In the period of the present contract from 14 April 1979 to 14 April 1980 the main effort has been on the experiments and related hardware and the development of instrumentation. This work has been in three major areas; (i) dilute chemical reactions, (ii) reactions with significant heat release in gases, and (iii) development of instrumentation, which we have summarized separately but their interdependence and common objective has been crucial and should be clear.

REPORT

I. Dilute Chemical Reactions in Turbulent Flow

During the past year, work on turbulent structures, mixing and chemical reaction has continued in the chemical mixing flow facility. This has concentrated largely on the origins and nature of the three dimensional structure. Particularly, in the case of the mixing layer, the unknown sensitivity of the mixing to initial conditions for various velocity ratios was explored. The effects of three dimensional perturbations on the initial vorticity distribution, its subsequent evolution, and on the mixing it accomplishes are of importance in optimizing a mixing device (as in the chemical laser, for example) and in modeling the flow. It was found that for a velocity ratio of unity the wake which forms downstream of certain trailing edge configurations consists of interconnected vortex loops which grow in the transverse dimension as they convect downstream but do not grow in the spanwise dimension, even at moderate Reynolds

number. Thus there are very large spanwise variations in the mixing over the entire test section length. The wake exhibits a long memory of the initial perturbations. In remarkable contrast, a shear layer (velocity ratio different from unity), formed with the same splitter plate geometry, very rapidly relaxes to its characteristic two dimensional large structure, quickly forgetting the initial three-dimensional perturbation.

In preparation for an attempt to measure chemical product flux in mixing layers a search was made during the present year for suitable reactants, the fluorescence of one of which is determined by the extent of the reaction. We have identified a suitable dye, sodium fluorescein, whose fluorescence when properly excited depends on the local pH. (See section III, Advanced Diagnostics and Instrumentation, Laser Induced Fluorescence.)

Application of this technique to a mixing layer, using laser light sheets to illuminate various sections of the flow, has resulted in excellent pictures which reveal the reactant-product structure. Besides its usefulness for such flow visualization studies of turbulent structure, the technique combined with laser Doppler anemometry should make it feasible to measure local product flux.

II. Energetic Chemical Reactions in Turbulent Mixing

Obtaining the effects of combustion with significant heat release on turbulent mixing and vice versa is a central objective of this contract. Towards this end substantial progress has been made during the last twelve months on the H_2-F_2 combustion facility and some final results obtained for the combustion of nitric oxide and ozone in a turbulent mixing layer. These are discussed separately below.

II.1. H_2-F_2 Facility.

The contraction section (nominally 27 x 10 x 48 inches) including screens, nozzle blocks and splitter plate has been completed and is in place. The design employs TFE Teflon, bonded to aluminum for the inner surfaces exposed to F_2. We thus achieved the extreme chemical resistance of teflon, a long-term, high-quality surface, and the rapid machining properties of aluminum. The test section (14 x 10 x 26 inches), where the mixing layer and reaction occur, required stainless steel. It has windows on four sides for optical instrumentation, a replaceable surface in the event of significant etching, and an enclosed and purged traversing mechanism for the initial mean temperature and velocity measurements. It has also been completed and assembled in place. It was designed to withstand atmospheric pressure so that the whole facility may be taken to vacuum pressures. The exhaust gas section is now partially fabricated. The processing and collection of the hot and highly toxic exhaust gases has been a major consideration. It consists of a 20 inch stainless steel tube supplied with 5% sodium hydroxide solution sprayed from a series of fogjets. This duct is then attached to two large teflon bags [10 feet x 14 feet], suspended outside the lab area, in which the cooled and partially neutralized exhaust gas and carryover spray will be collected. A small system to subsequently scrub these gases and discharge to atmosphere has been designed. Another area of major concern has been the detailed plumbing of the F_2 and H_2 lines. The risk of fire and the supreme importance of safety have required the most careful consideration. This has resulted in a system in which no pure fluorine will enter the laboratory and all mixing with the carrier gases will be done remotely in

smaller volumes and at higher pressures outside, before transfer to the blow-down volumes within the laboratory. Recently Mr. D. L. Bond of J.P.L. and Mr. M.E. Guenther of Edwards AFB inspected the partially assembled facility and offered very helpful advice. In an informal report they comment "They are taking reasonable precautions and should be able to perform their experiment with a high degree of safety."

All components have now been ordered and it is expected that early non-reacting runs will be made in the facility before July 1980.

II.2. Present results in the NO-O_3 mixing layer and a model comparison.

Under the sub-contract to the University of Adelaide Mr. Wallace has worked in close contact with Professor Brown and obtained a number of results. The mean temperature and velocity were obtained in more than thirty separate runs to date. In particular these results include a series in which the concentration ratio in the two streams was held approximately constant while the absolute concentration increased from 0.5% to 10% O_3. The maximum mean temperature in the layer rose to approximately 200°C. The effect of the heat release was very marked, particularly its effect on the entrainment rate. Similarly a series of runs were made at a low concentration of NO (.5%) while the O_3 concentration was increased from .5% to 5%. In this dilute reactant case a direct comparison could be made with predictions from previous p.d.f. measurements in the non-reacting case. The agreement was moderately close but very far from what would be predicted by conventional models.

Lastly the effect of free stream density ratio was observed by holding the concentration of NO and O_3 fixed and changing the NO diluent from nitrogen to helium. The effect was dramatic, quite unlike that which simple

models would predict and a direct result of the effect of density ratio on entrainment. Since the effect of high heat release is to produce large density changes and since many applications involve free streams of different density these effects seem highly relevant.

The extent to which the $k-\varepsilon\Pi$ and the $k-\omega$ turbulence models (as developed for the Army Research Office for the prediction of reacting turbulent flows) were able to predict these results is shown in the attached figure 1. The computations were made by Dr. B.J. Walker of ARO who spent a sabbatical year at GALCIT during this contractual period. These are early comparisons but there is no doubt that the enormous difference between measured and predicted mean temperature rise is, amongst other possibilities, related to the inadequacy in the models with which the reactant probability density function is either modeled or incorporated.

III. Advanced Diagnostics and Instrumentation

III.1. Laser induced fluorescence

Laser induced fluorescence has been employed in plane mixing layer flows, in conjunction with other related research efforts, to investigate the three-dimensionality of the large vortical structures in the flow, as well as phase locking phenomena when a small periodic disturbance is introduced in the shear layer free streams. This unique flow visualization technique allows a slice to be made through the turbulence, permitting a single plane to be labeled by the illuminating laser and the intersection of that with the dyed fluid to fluoresce. The example in figure 2 corresponds to a small amplitude, periodic excitation of one of the two free streams, and is a picture of the labeled plane at roughly mid-span in the shear layer. In addition to such measurements, chemically activated laser induced fluorescence has also been used to label the chemical product in a reacting shear layer directly. Both still and motion picture photography have been used for preliminary qualitative measurements.

III.2. Multichannel-multipoint laser Doppler velocimetry.

The electronic set-up for a four-channel measuring system is shown in block diagram in figure 3. The six stages of the system are indicated by numbers below the corresponding stage.

The first stage consists of an appropriate photodetector assembly, typically silicon avalanche photodiodes coupled to matched transimpedance amplifiers. Each photodiode detects the light scattered from the corresponding focal volume, as selected by the collection optics, and converts it to an output current. The transimpedance amplifiers (stage 2) are contained in the same housing as the photodetectors to minimize stray capacitance and electromagnetic interference (EMI).

The outputs of the transimpedance amplifiers are then fed into 2 dual amplifier/multiplexors (stage 3). The dual amplifier/multiplexors provide the remaining necessary gain and select one of the input signals according to the state (HI,LO) of the corresponding channel select lines. This has the advantage of reducing the electronics downstream of the amplifier/multiplexor in half, at the expense of reducing the maximum data rate at the input. We anticipate that this will not comprise the actual data rate by an appreciable amount, as that is limited by the scattering particle flux. In any event, multiplexing at the front end can be optionally disabled under software control, should this be dictated by the measurements.

High and low pass filters are then used to filter out noise away from the anticipated signal frequencies being measured (stage 4).

The analog processor (stage 5) applies a series of analog tests to the prefiltered analog signal as a partial means of identifying signal dropout. If the signal passes the tests, the analog processor generates a digital signal on the zero crossings of the analog signal for further processing by the digital processor. The analog processor also generates the channel select signal to switch channels after the end of a Doppler signal burst from the previous channel. Finally, the analog processor is interfaced to the Device Bus to allow the various processing parameters (levels, modes, etc.) to be set by the computer central processing unit (CPU). Two analog processors are included on one card as shown by the dotted line. Four of these have been partially fabricated, as photographed in figure 4.

The digital processor (stage 6) takes the digitized burst and computes the duration and number of cycles (period) of the burst. In addition,

the duration of the successive cycles within a burst are compared to provide an additional check on the validity of the data. It is required that successive periods must be equal to within a maximum percentage difference, otherwise the burst is discarded, or read out as two or more bursts, depending on the operating mode. The results are stored in a First-In-First-Out buffer (FIFO) to allow the next burst to be processed with no dead time, while the previous burst data are being read out. The digital processor is also interfaced to the Device Bus to allow the computer CPU to read data and set the processing parameters and mode of the digital processor. Two digital processors are included on one card, as shown by the dotted line. See also figure 5 for a completed unit.

Finally, an interface between the Device Bus, which interconnects the processing sections, has been fabricated to allow an LSI-11 based computer to access the LDV processor. See figure 6. This permits the CPU to read from and write to devices on the Device Bus. The card also notifies the CPU if more than one device has output data available. This card also incorporates a programmable clock (up to 200Mhz) which is used as a two-phase time base (2.5ns resolution) on the digital processors to time the LDV burst periods (upper right hand corner of figure 6).

III.3. Particle streak velocity field measurements.

As was stated in the original proposal, the driving motivation behind the multi-channel LDV was to allow something better than point velocity measurements, in view of the need for velocity field information. Running alongside the multi-channel LDV effort, we have been attempting to fill this need by a new method using particle streak image processing. A plane (say x,y) of interest is illuminated by a laser sheet and a time exposure

photograph is taken of controlled size particles in the flow. See figure 7. If the velocity component perpendicular to the illuminated plane is small enough so that the particles do not cross the width of the laser sheet during the exposure, the streaks indicate the direction and magnitude of the local velocity vector. The resulting negative is scanned, using the RETICON array image acquisition system previously developed under this contract, and read into the LSI-11 based computer data acquisition system (1024 x 2,500 pixels). The digital image data are now processed to yield the streaks, which are fitted with a least squares estimate of the best parabola for each one. The length and slope of each parabola then provides an estimate of the magnitude and direction of the local velocity. A two-dimensional grid is then defined on which the velocity is evaluated. See figure 8. Figure 9 represents the velocity field in translating frame in which the now obvious vortices are stationary. We believe that this method holds great promise and complements the LDV effort permitting the instantaneous velocity field to be measured in one plane at time, for flows that are primarily two-dimensional.

III.4. Acoustical imaging

Processing electronics to measure amplitude and phase of a sound wave after having passed through a given flow field have been designed, tested and fabricated to a large extent. The acoustic recording medium is a linear sensing array containing 100 individual piezoelectric elements (figure 10). Each element measures .035" x .5" to give a total length of 3.5". After parallel processing of all output signals, the resulting amplitude and phase information is written sequentially on magnetic tape at a rate of 500 frames/sec.

A block diagram of the electronic system is shown in figure 11. The

basic circuit element is a phase sensitive detector, whose output is proportional to amplitude and phase of the input signal with respect to some reference signal. Hence, by making two measurements with two reference signals 90° out of phase to each other, one obtains amplitude and phase of the input signal. The reference signals, designated as "SIN" and "COS" are locked to the acoustic driving signal through a phase-locked-loop circuit. The driving signal itself is provided by a function generator, whose output is amplified to power the acoustic emitter. On the receiving side, we have the piezoelectric array whose signals are amplified and fed into the phase sensitive detector circuits. Using 96 array elements requires 192 detector circuits, which are multiplexed into 24 8-bit A/D converters. An address generator supplies the channel address which is decoded at every A/D converter, activating only one at a time. The common output data bus feeds the digital information through a high speed buffer memory to the magnetic tape.

Figure 12 shows the setup for testing the prototype circuit board, which is seen in the center. One such printed circuit board is capable of processing four array signals. The rack to the right contains a phaselock generator, power supplies, and a test oscillator. Beneath are the power amplifier, an auxiliary oscillator, the phase-locked-loop-circuit, the address generator and an output display unit, where the latter three units were fabricated specifically for this system. The high speed buffer memory, a printer and the tape recorder can be seen on the far right. The acoustic emitter is located in the far back, while the two oscilloscopes on the left monitor input and output of the processing electronics.

A prototype system using four out of 100 piezoelectric array elements has been built and tested at a sound frequency of 300 kHz. Fabrication

of the printed circuit boards required to use 96 elements is under way.

IV. List of Professional Personnel

Hans W. Liepmann	Ph.D.	1938	University of Zurich
Garry L. Brown	Ph.D.	1967	University of Oxford
Paul E. Dimotakis	Ph.D.	1973	California Institute of Technology
Anatol Roshko	Ph.D.	1952	California Institute of Technology
Robert E. Breidenthal	Ph.D.	1978	California Institute of Technology
James E. Broadwell	Ph.D.	1950	University of Michigan

V. Lectures and Seminars

R. E. Breidenthal	American Society of Mechanical Engineers Meeting San Diego, CA July 1979 University of California, Berkeley, CA Sandia Laboraotry, Livermore CA University of California, Los Angeles American Physical Society Meeting Notre Dame November 1979
G. L. Brown	Second Symposium on Turbulent Shear Flows Imperial College, London July 1979 Sandia Laboratory, Livermore, CA Stanford University, Stanford, CA Fluid Mechanics Seminar, Caltech AIAA Meeting, Pasadena, CA January 1980
P. E. Dimotakis	Boeing Symposium on Air Flow Instrumentation Seattle, WA February 1980 Research Directors Conference, Caltech February 1980 Princeton University, Princeton, NJ Fluid Mechanics Seminar, Caltech
H. W. Liepmann	AGARD Symposium on Turbulent Boundary Layers - Experiments, Theory and Modelling The Hague, Netherlands, Sept. 1979 IUTAM Meeting, Stuttgart, Germany, Sept. 1979
A. Roshko	Second Symposium on Turbulent Shear Flows Imperial College, London, July 1979

VI. Publications

P. E. Dimotakis, D. J. Collins, and D. B. Lang, Measurements in the Turbulent Boundary Layer at Constant Pressure in Subsonic and Supersonic Flow, AEDC-TR-79, July 1979.

P. E. Dimotakis, M. M. Koochesfahani, C. J. Catherasoo, M. Gharib, and D. B. Lang, Two-Point LDV Measurements in a Plane Mixing Layer, AIAA Jour. 17, 12, p. 1347, December 1979.

L. Bernal, R. E. Breidenthal, G. L. Brown, J. H. Konrad, and A. Roshko, On the Development of Three-Dimensional Small Scales in Turbulent Mixing Layers, Second Symposium on Turbulent Shear Flows, Imperial College, London, July 2-4, 1979

B. A. G. Delcourt and G. L. Brown, The Evolution and Emerging Structure of a Vortex Sheet in an Inviscid and Viscous Fluid Modelled by a Point Vortex Method, Second Symposium on Turbulent Shear FLows, Imperial College, London, July 2-4, 1979.

R. E. Breidenthal, Response of Plane Shear Layers and Wakes to Strong Three-Dimensional Disturbances, accepted by Physics of Fluids.

R. E. Breidenthal, A Chemically Reacting, Turbulent Mixing Layer and Wake, submitted to Journal of Fluid Mechanics, February 1980.

R. E. Breidenthal, Response of Plane Shear Layers and Wakes to Strong Three-Dimensional Disturbances, submitted to IUTAM for August 1980 meeting in Toronto.

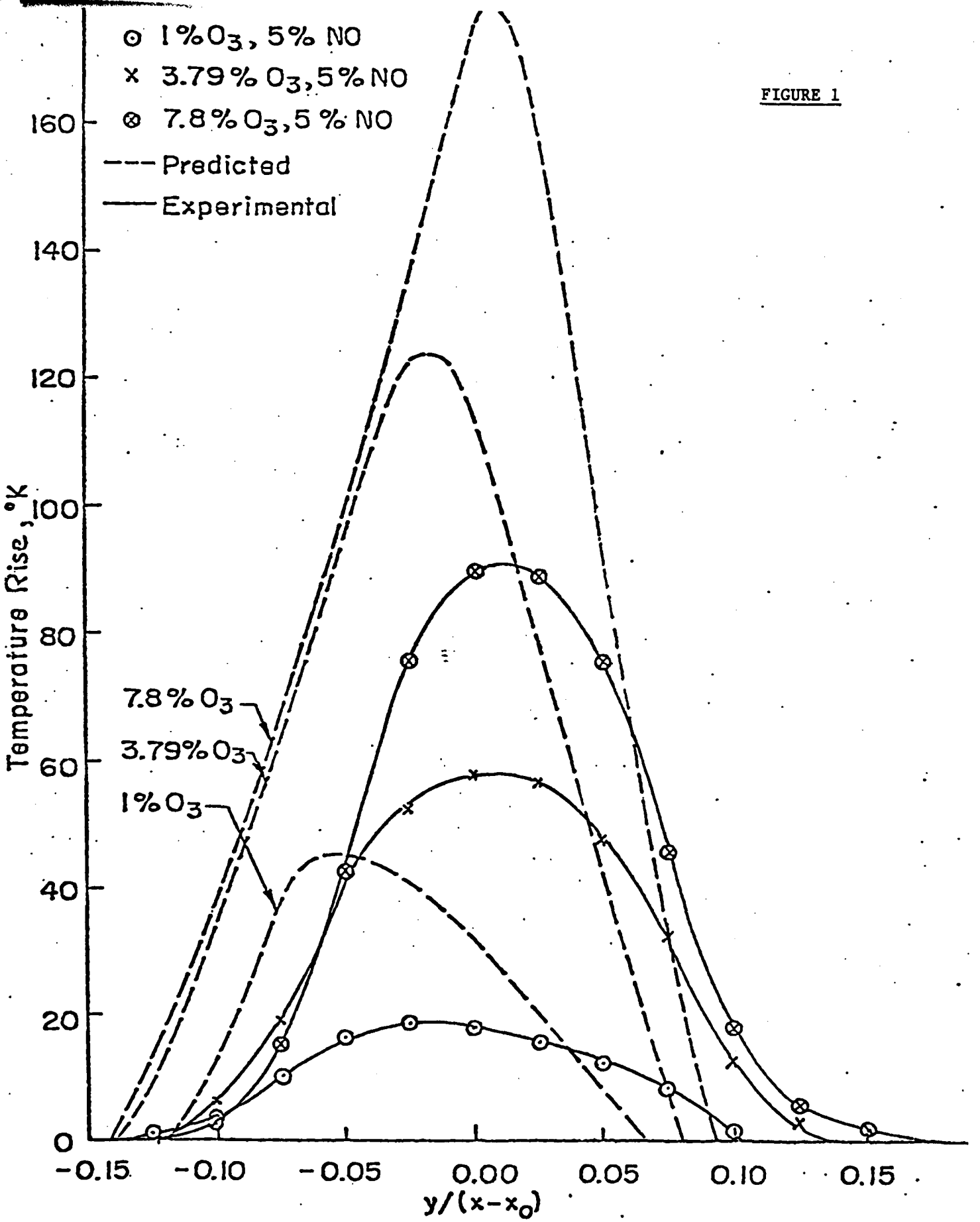

FIGURE 1

MEASURED AND PREDICTED TEMPERATURE DISTRIBUTION IN SHEAR LAYERS BETWEEN NITRIC OXIDE AND OZONE

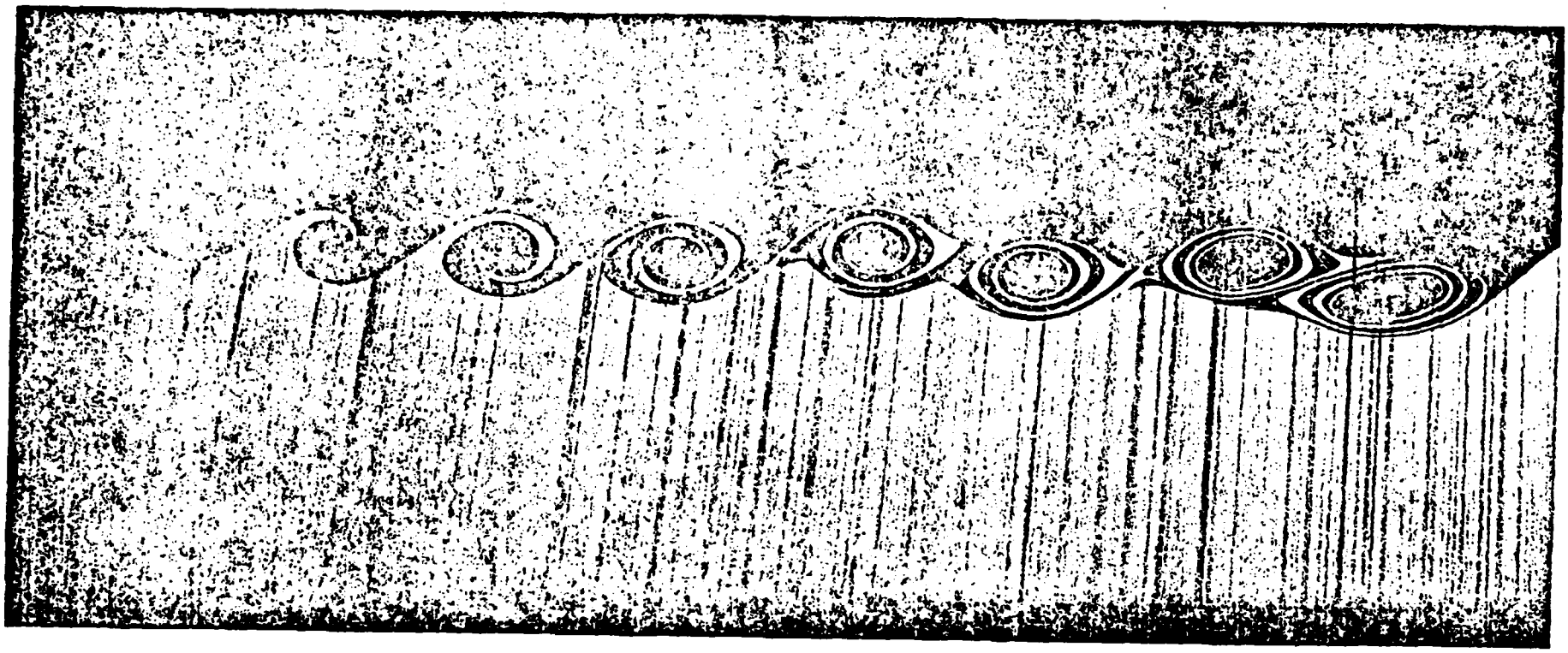

Fig. 2 Shear induced fluorescence (x,y) plane cut of a two-dimensional shear layer with periodic excitation (photograph by R. Roberts).

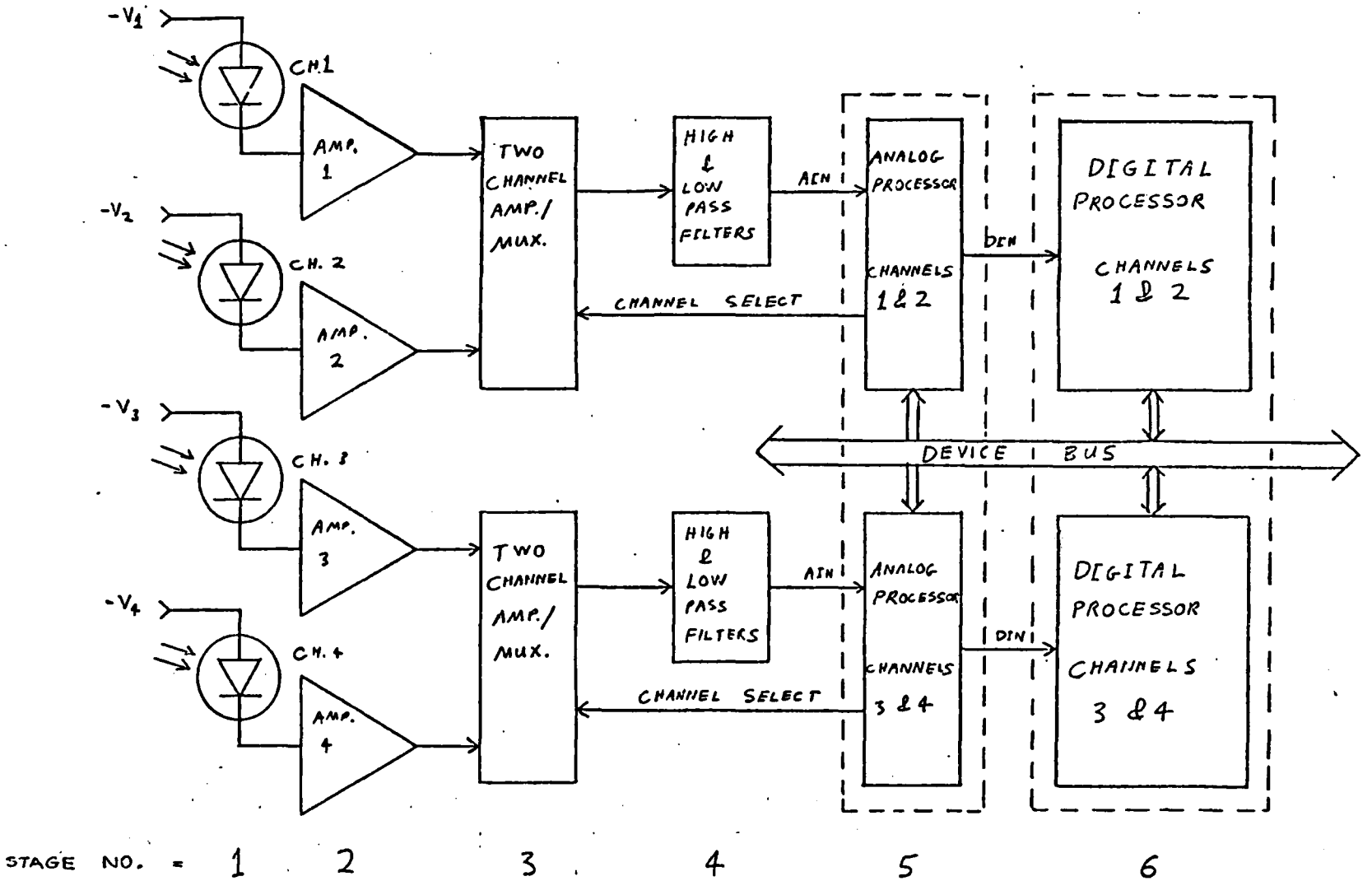

Figure 3. Processing electronics block diagram.

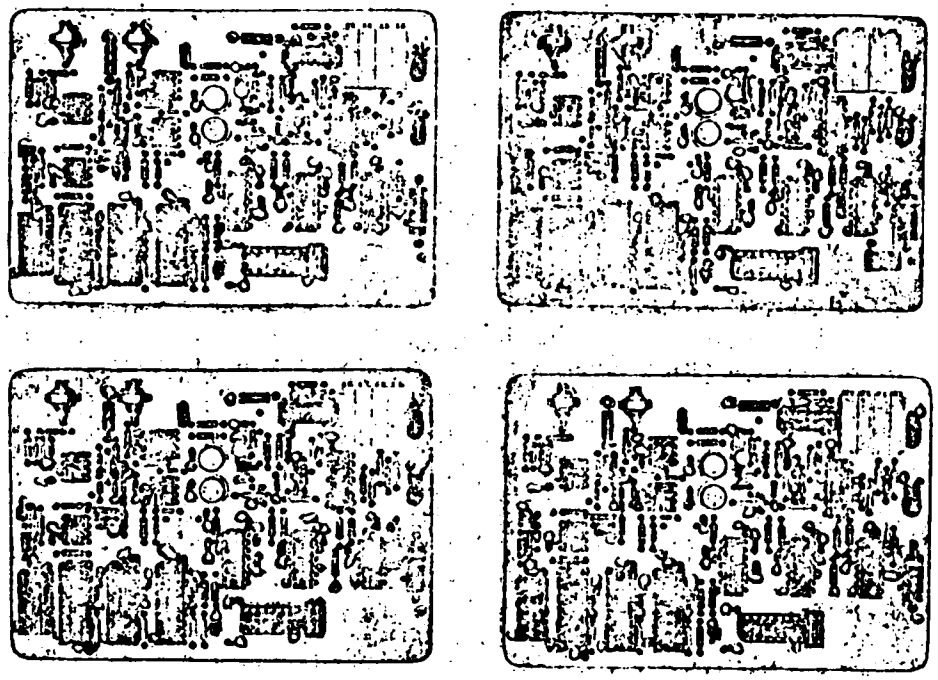

Figure 4. Analog processors (4 channels).

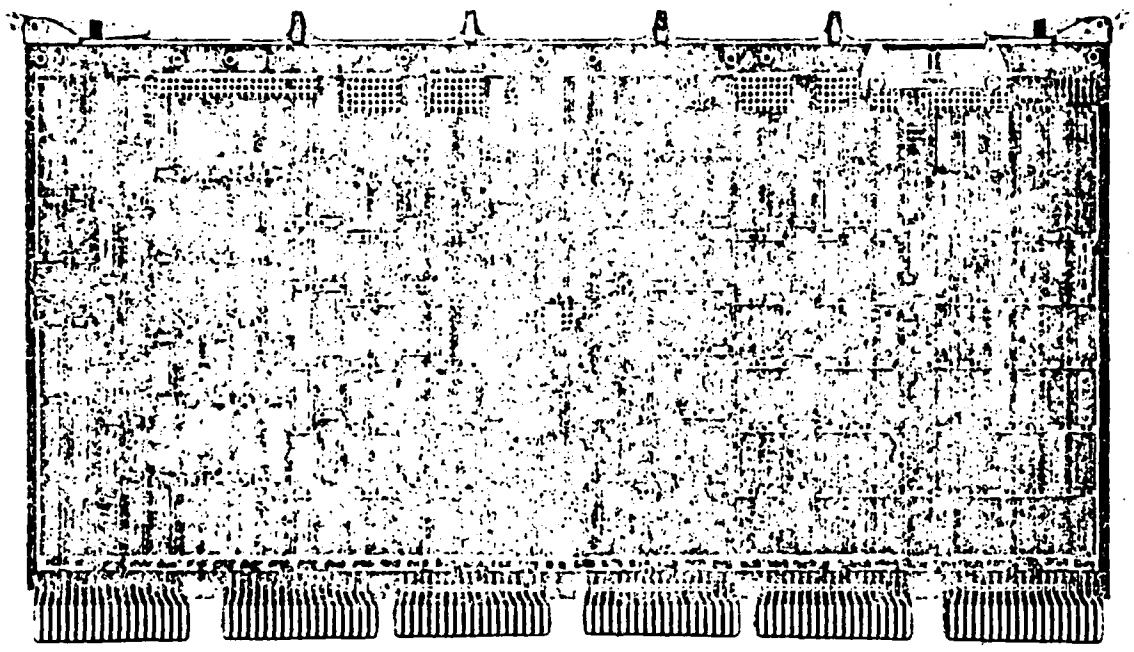

Figure 5. Digital processor (2 channels).

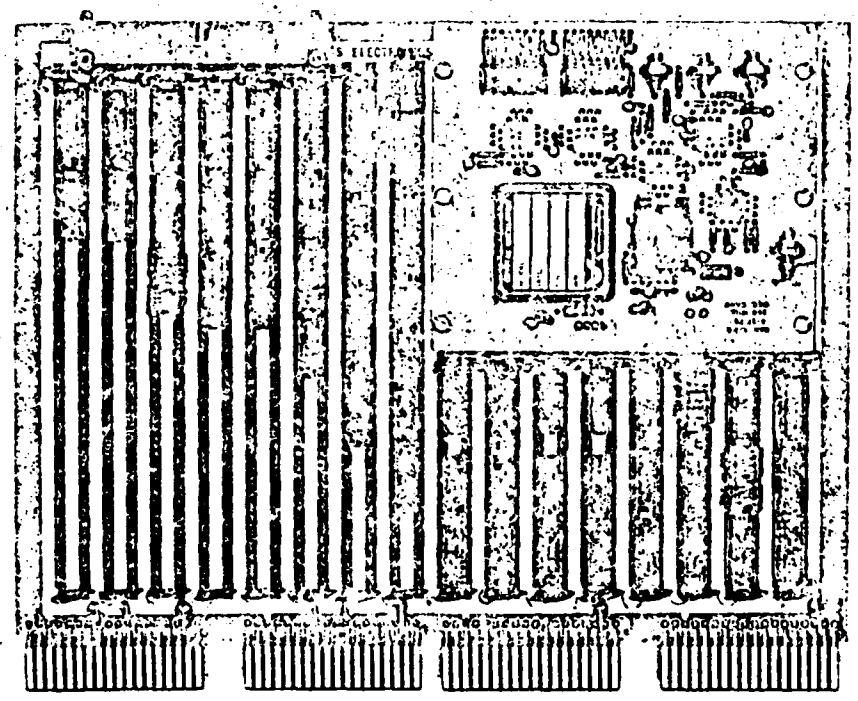

Figure 6. Programmable time base and Device Bus interface card.

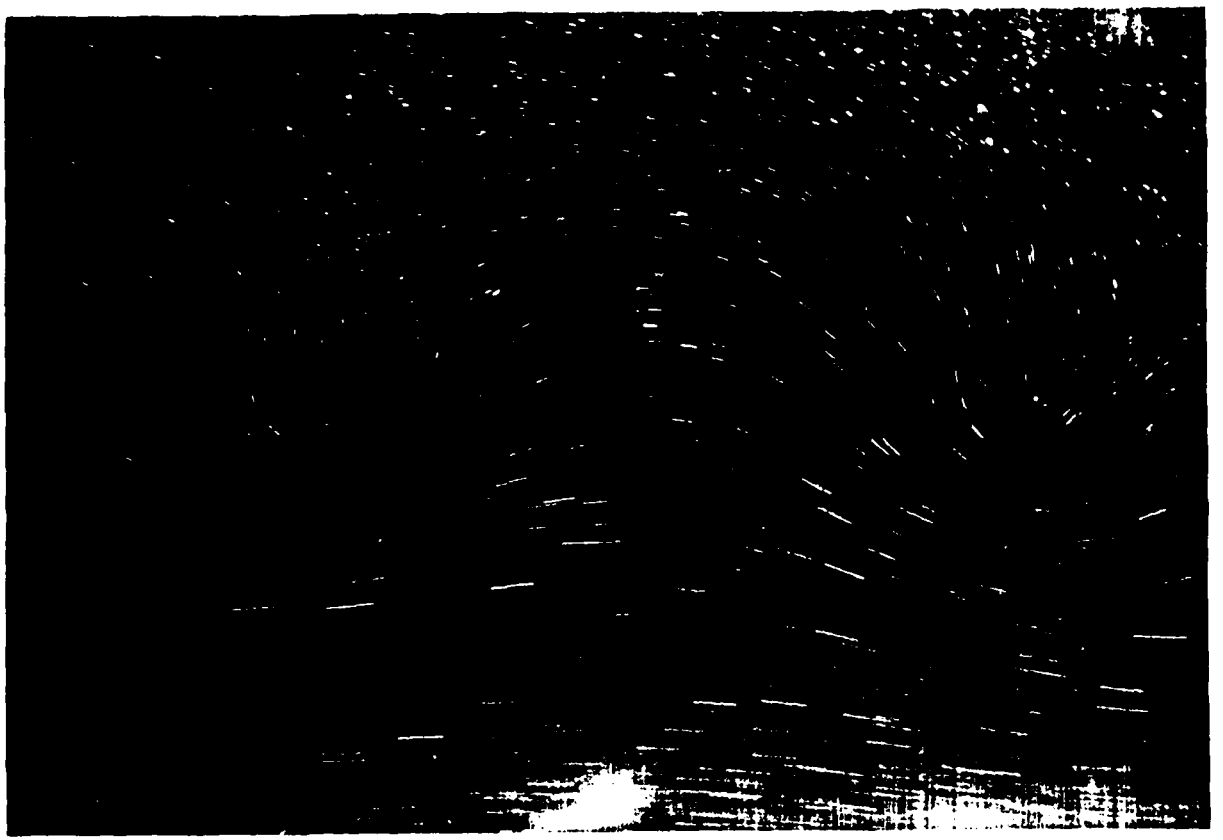

Fig. 7 Particle streak photograph of a two-dimensional shear layer.

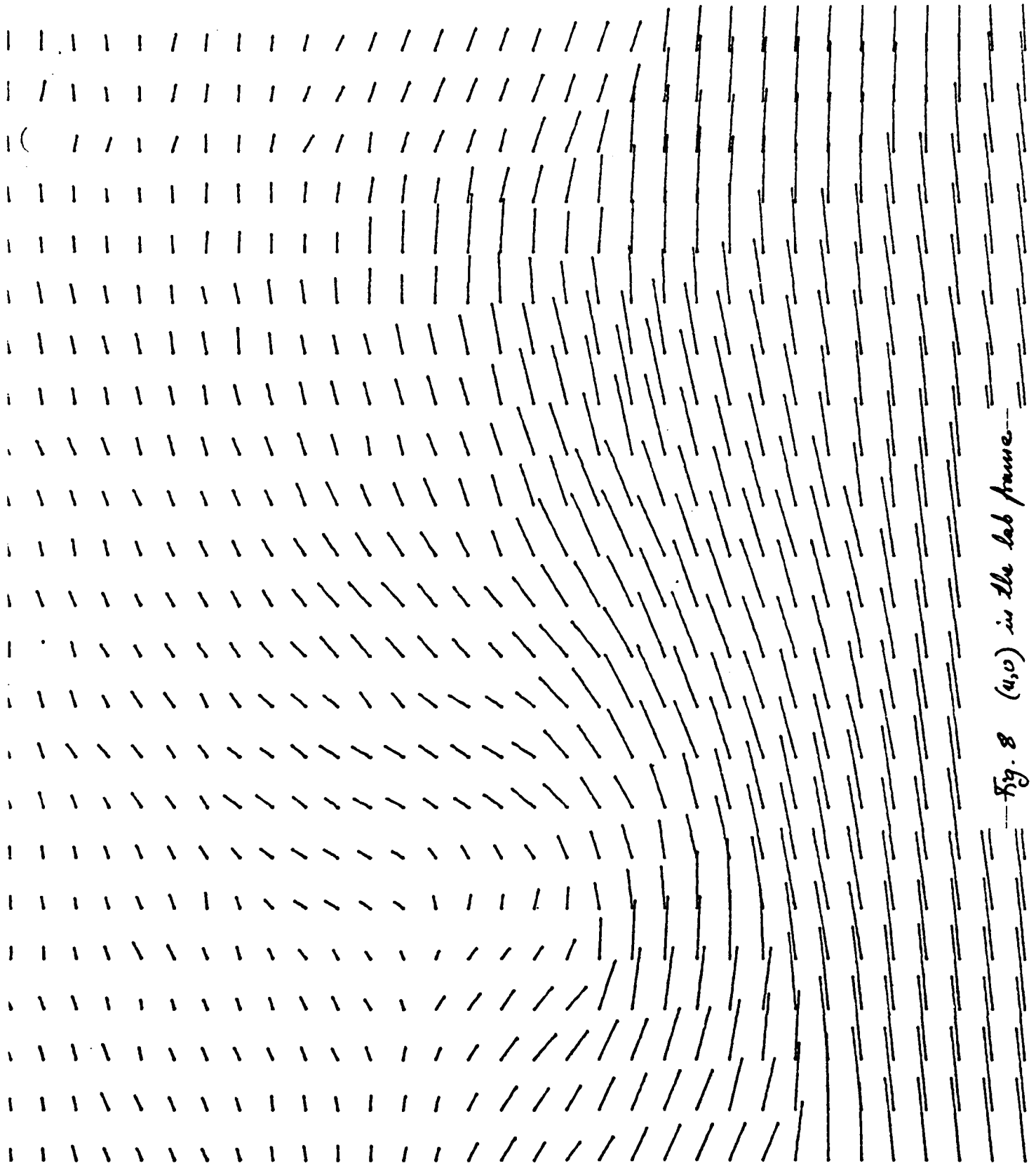

Fig. 8 (u,v) in the lab frame

Result of GRIDV (using FILD4)

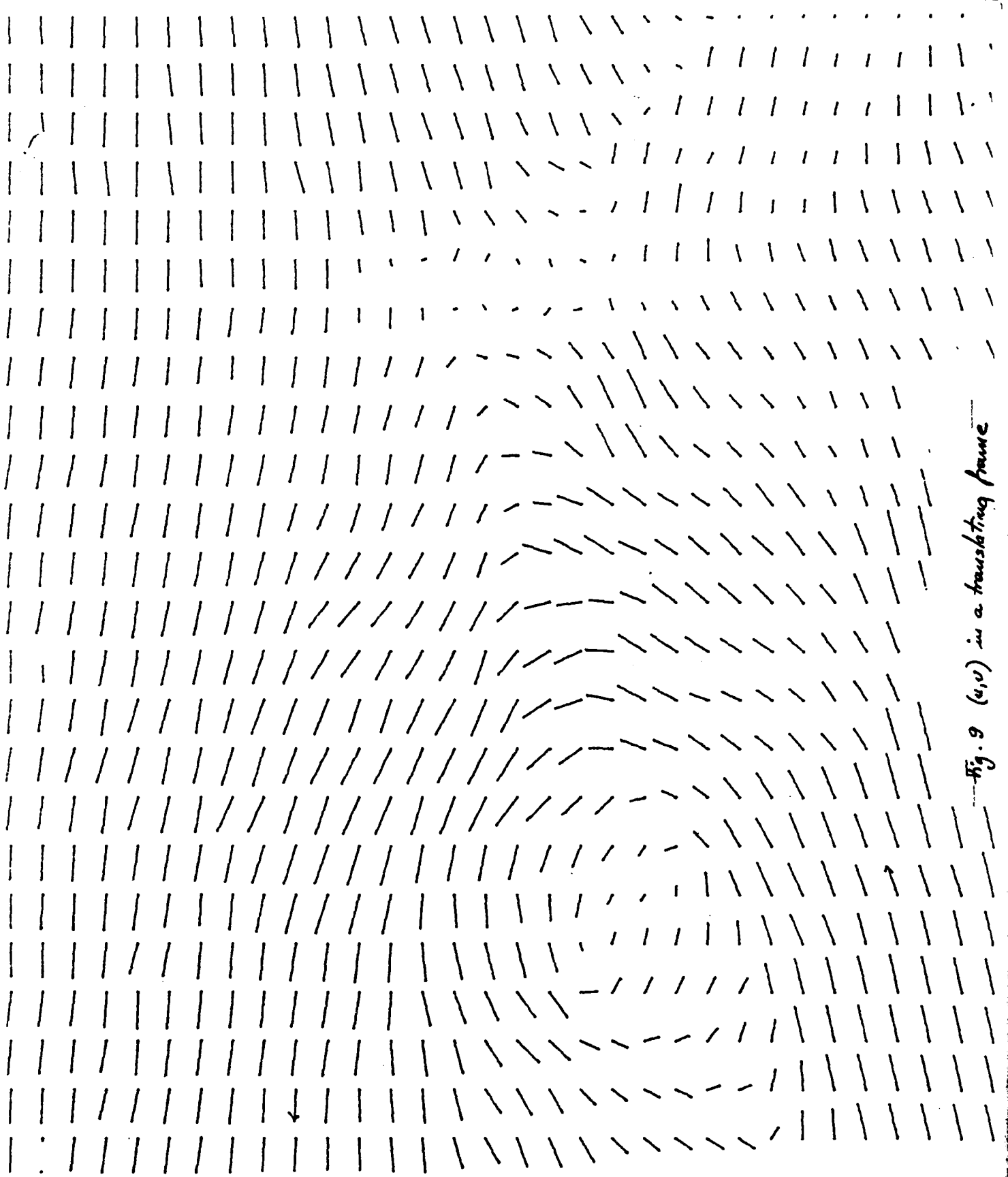

Fig. 9 (u,v) in a translating frame

Result of GRIDR (using FILDG)

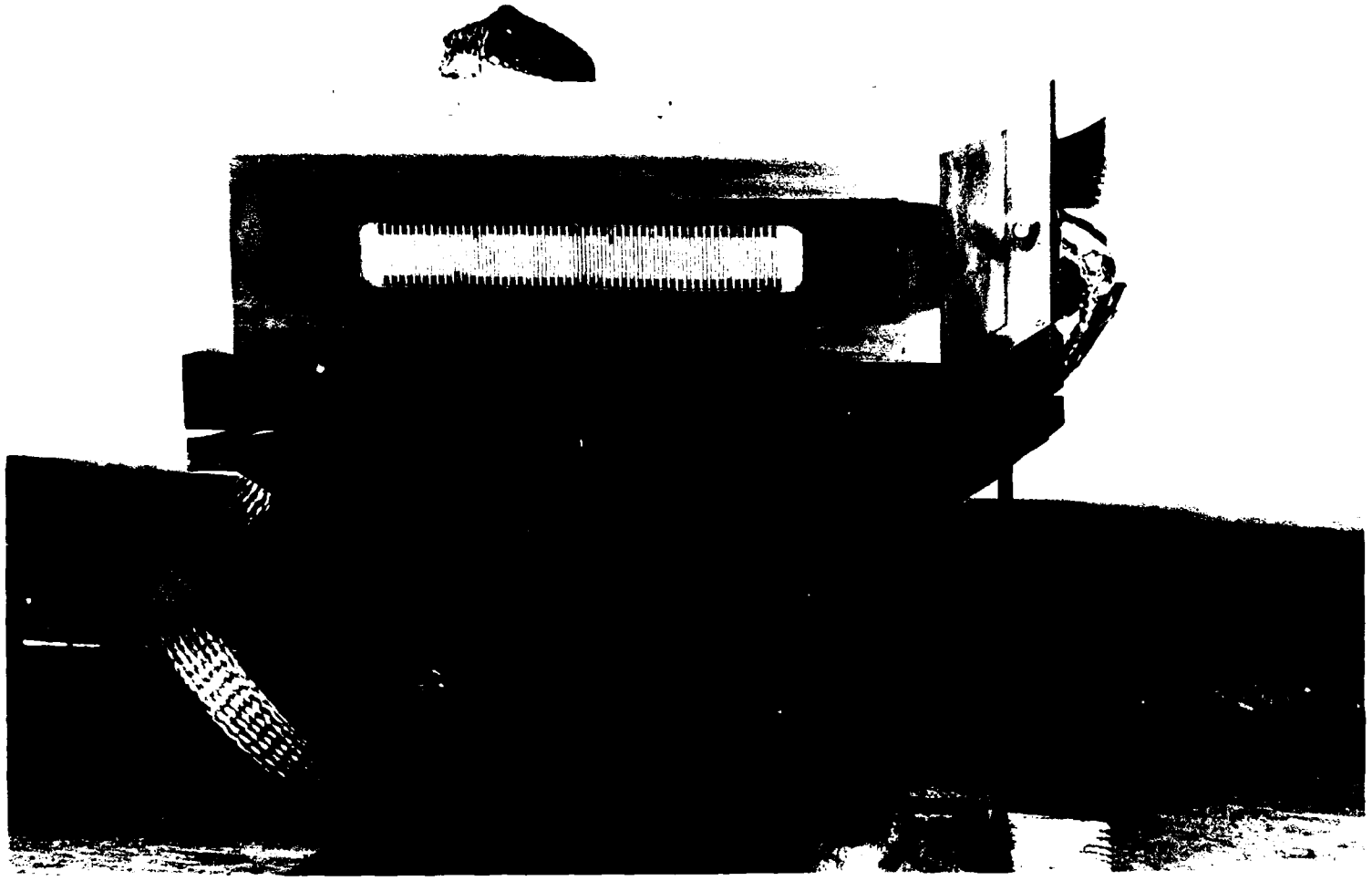

Figure 10. Piezoelectric Sensing Array

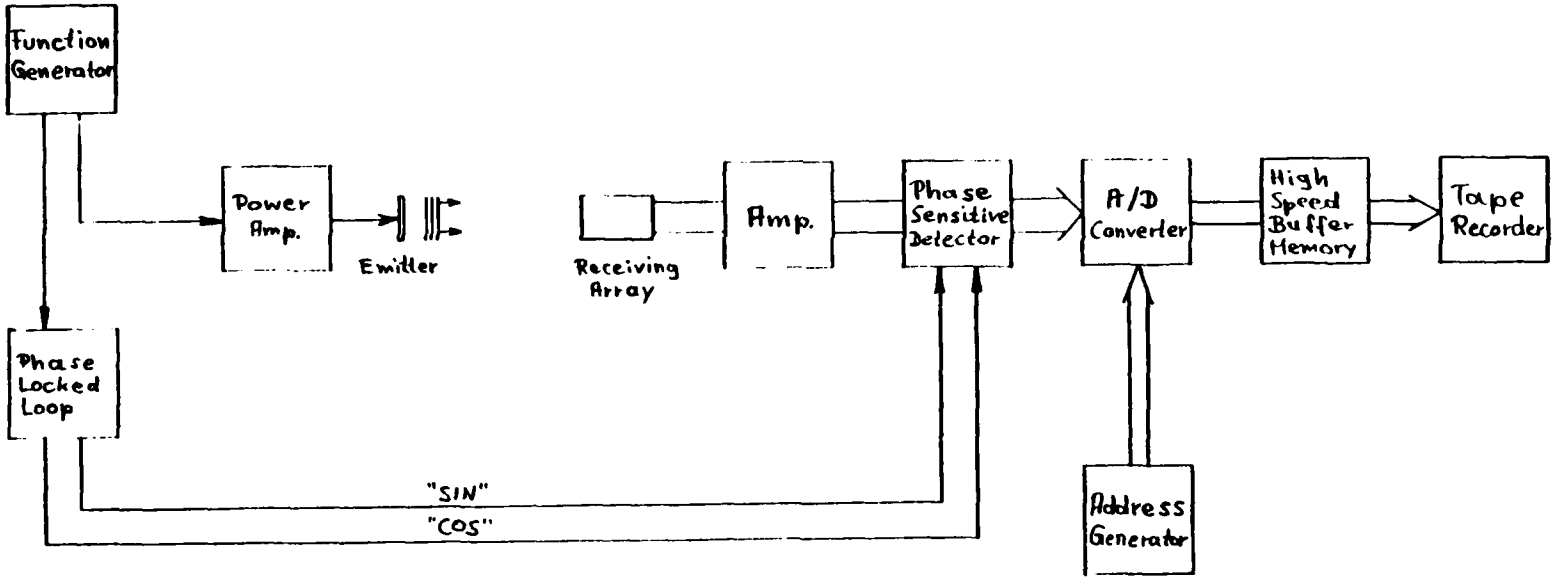

Figure 11. Data Processing and Acquisition

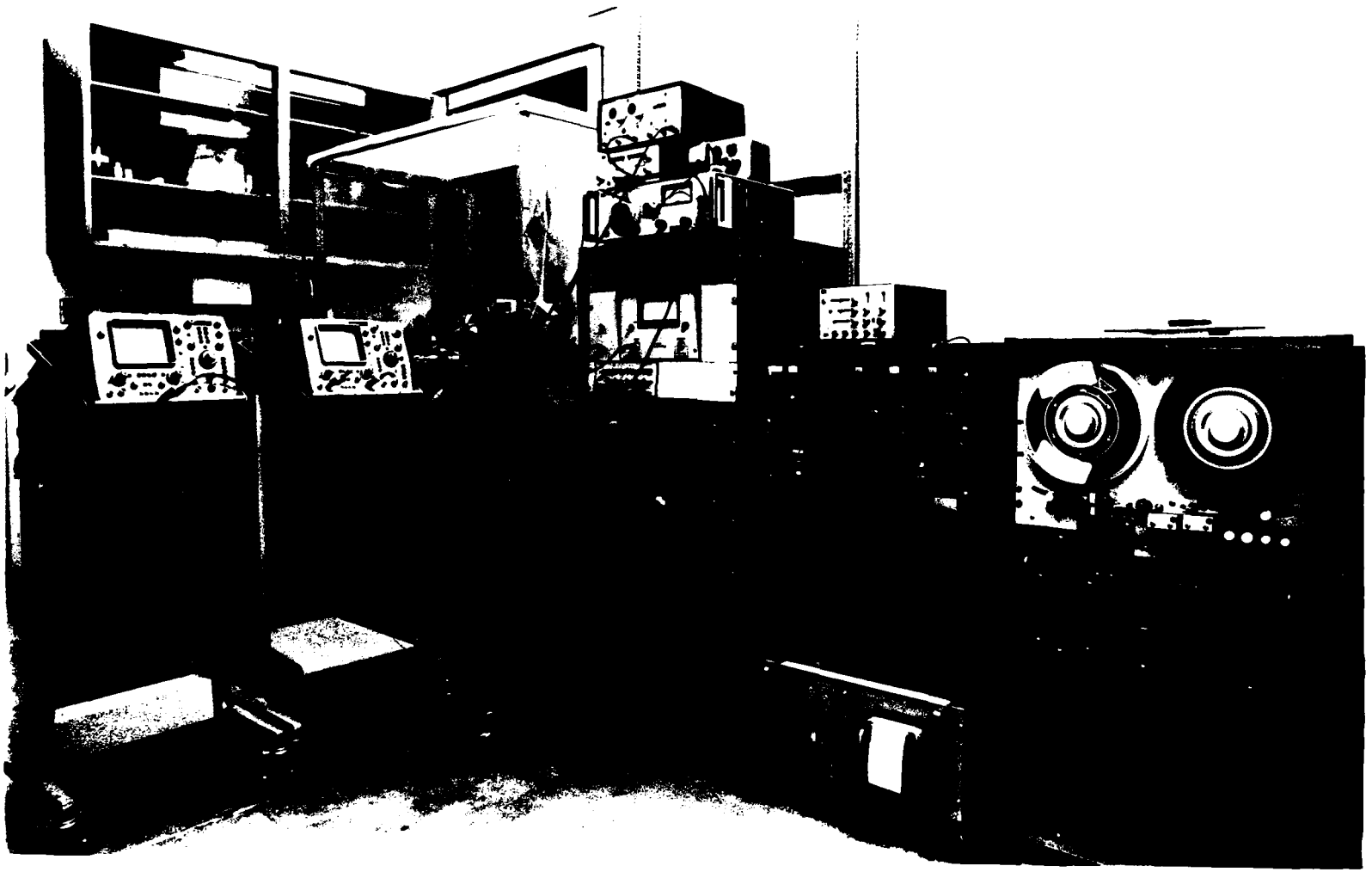

Figure 12. Data Processing and Acquisition Hardware